Orion Capsule Parachute Assembly System (CPAS) Riser Twist Load Amplification

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Any cluster of parachute systems is subject to effects on performance due to interactions between the parachutes. One such interaction is the twisting of a riser from one parachute around that of another. Due to friction and relative motion between the risers, it is possible for the tension in the riser near the attach point to be different from the tension in the riser towards the suspension lines or canopy. This could result in system failure due to larger than expected loading. The Orion Capsule Parachute Assembly System (CPAS) designed and executed a test to quantify the amplification of the load in a parachute riser due to twist, rocking rate and angle, cluster size, and canopy load. The design of the testing approach, test matrix, and hardware are discussed along with results and findings.

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I. Introduction

The Capsule Parachute Assembly System (CPAS) utilizes 11 parachutes to safely slow the Orion capsule for a splashdown in the ocean. The deployment sequence is illustrated in figure 1. Three Forward Bay Cover Parachutes (FBCPs) are mortar-deployed to begin the process of slowing the Command Module (CM). They provide sufficient force to ensure that the Forward Bay Cover (FBC) will continue to translate away from the capsule through the wake, mitigating the risk of recontact with the capsule and the deploying drogue parachutes (or pilot parachutes in a low-altitude abort case). Two drogue parachutes slow and stabilize the CM for main parachute deployment, except for low-altitude aborts. Three main parachutes are each deployed by separate pilot parachutes. The main parachutes stabilize and decelerate the Orion CM to a speed safe for splashdown. Due to vehicle dynamics, the drogue and main risers may twist around each other after deployment.

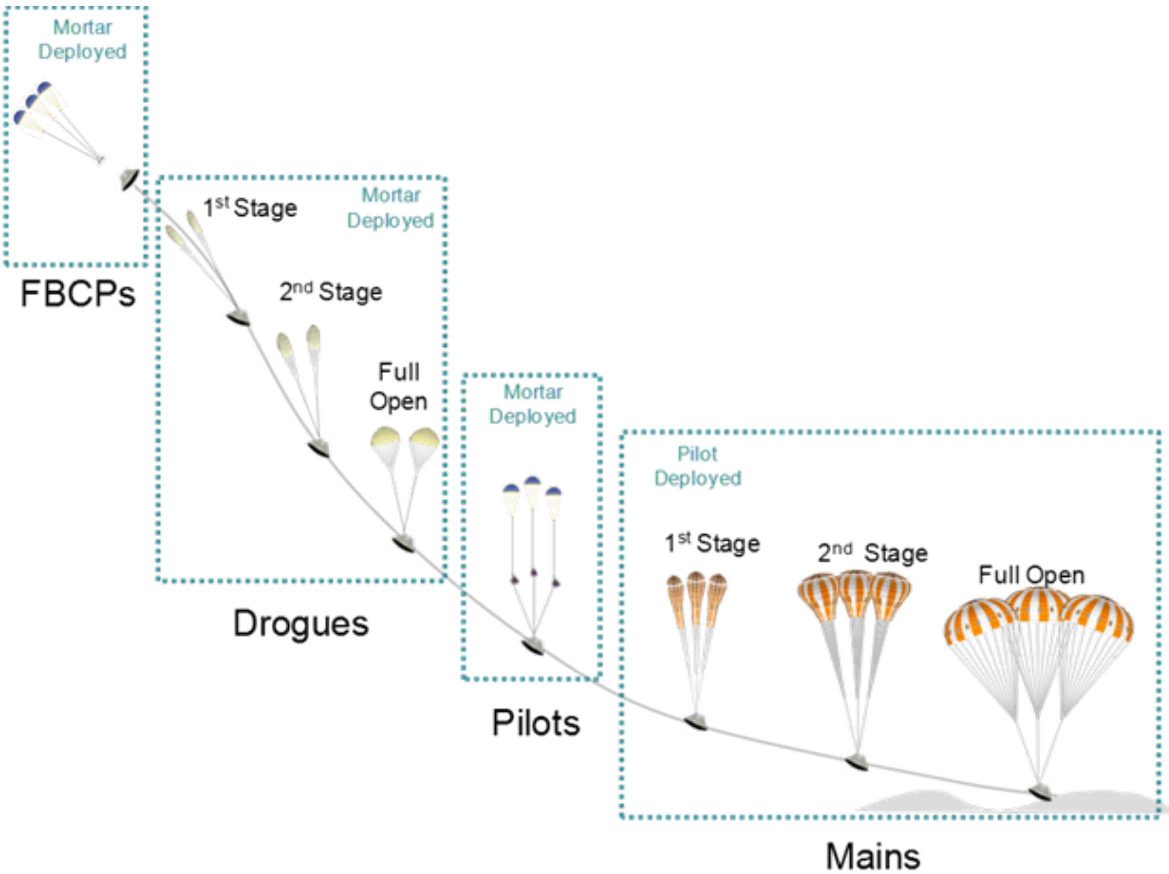

Fig. 1 CPAS Concept of Operations

The drogue and main risers are the most at risk for twisting around each other after deployment. Diagrams of the primary components of the drogue and main parachutes are shown in figures 2 and 3, respectively. The suspension lines are continuous from the canopy to the riser extension. The suspension lines converge from the canopy to a confluence point. Between the vehicle and the confluence the bundled suspension lines are called the riser. Riser extensions are used between the connection to the vehicle (at the concentric pins) and a point far enough away from the vehicle that contact is unlikely. Riser twist will occur only on the riser extensions. The extensions are used so that a pre-determined section of the riser can be replaced after drop tests, but the extensions are used in the flight configuration for consistency. The riser extensions are cut during drop tests and flight. In this report the term “riser” will often be used instead of “riser extension” for brevity. The end of the riser that connects to the vehicle through the concentric pins is sometimes called the “south” end, while the canopy end of the suspension lines is called the “north” end.

The Orion CM can experience a continuous roll rate with deployed parachutes and the parachute cluster will not

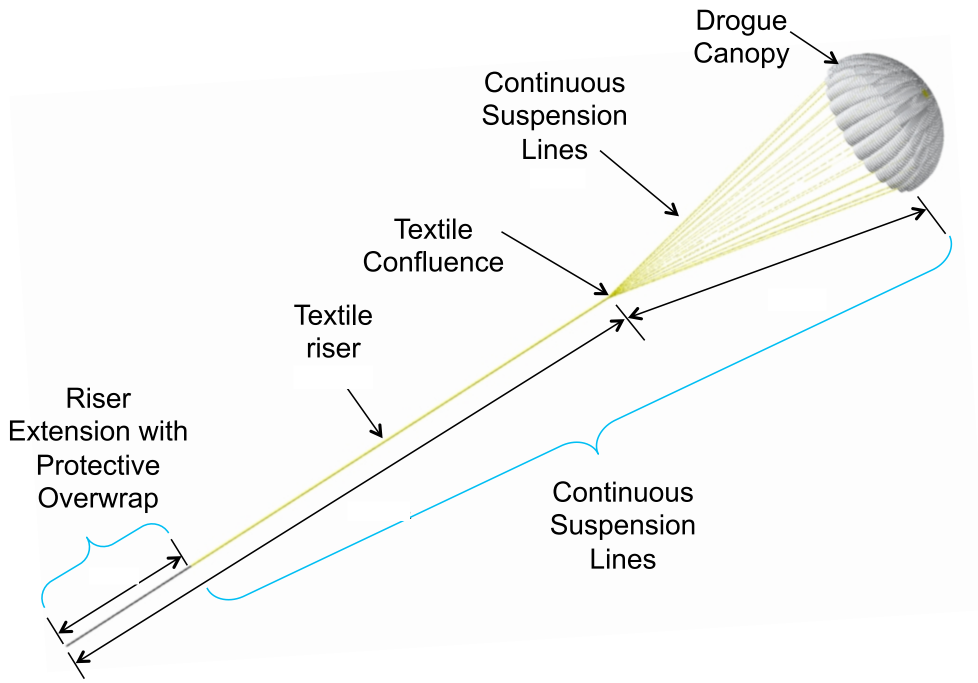

Fig. 2 Drogue Diagram (modified from [1])

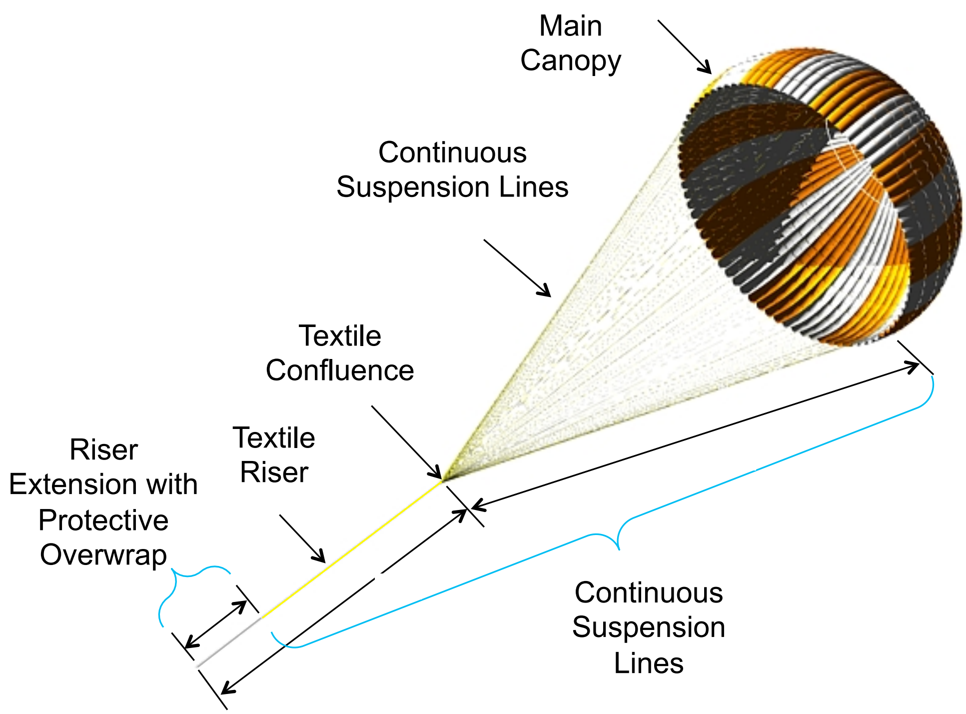

Fig. 3 Main Diagram (modified from [1])

normally rotate at the same rate as the capsule which results in the risers twisting around each other, as seen in figure 4. The roll rate can be caused by a combination of aerodynamic forces, offset center of mass, and the offset drogue parachute attachment points. Additionally, due to the close proximity of the risers at the fairlead, there is limited restoring moment against the twist, allowing the twist to be easily initiated and sustained, as seen in figure 5 in which riser load share and twist are plotted as a function of time. The restoring moment of the twist is small compare to the vehicle rotational inertia.

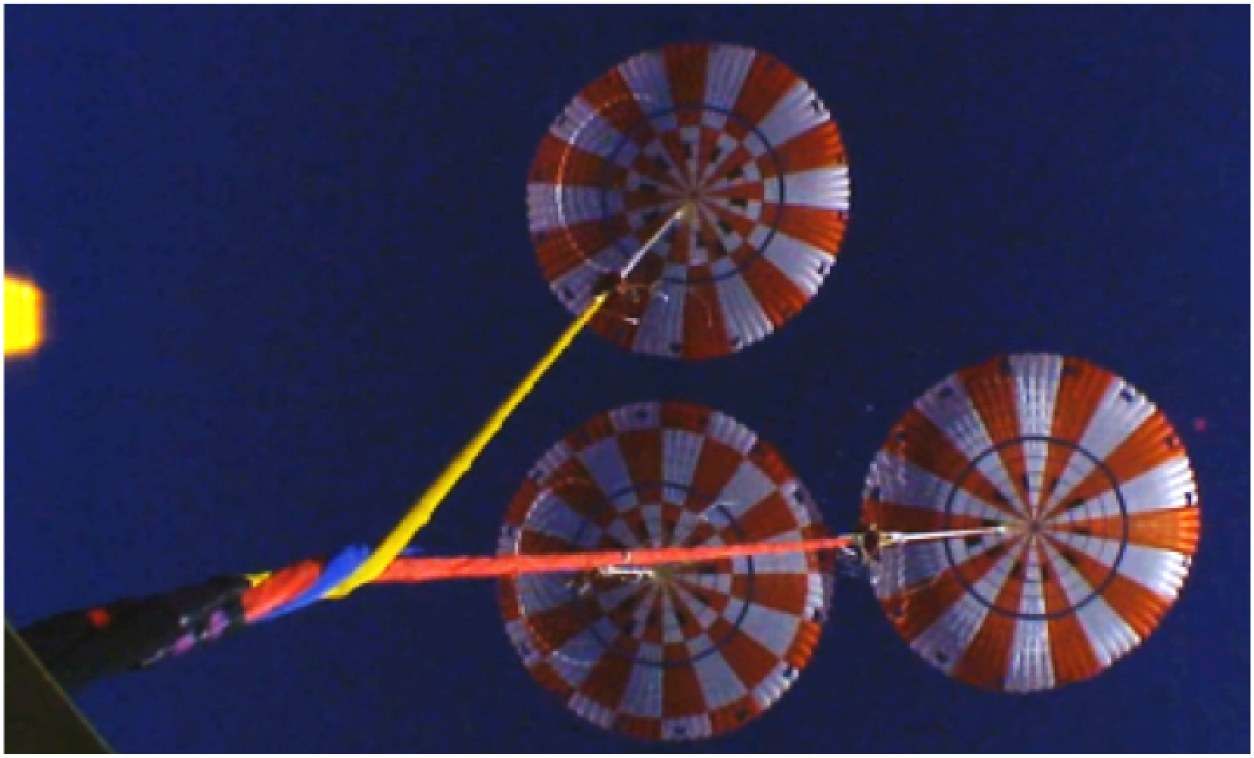

Fig. 4 Twist in CPAS Main Parachute Risers

A schematic showing the definition of twist angle is shown in figure 6. The main risers are represented as the green, blue, and red cables. The fairlead is the represented as the disc with a hole in it. Zero twist angle is shown in the left image where the risers simply bend around the fairlead and remain in plane with the point where the enter the gusset. The twist angle is shown in the right image. The risers are twisting around each other and at some point spread out in different directions and contact between the risers stop. This graphic uses the blue riser as reference, and the twist angle is measured from the vertical plane of the blue riser gusset hole and angle where that the blue riser departs from the twisted riser group.

While the damage directly to the risers due to force and friction from twist alone are mitigated by the riser protection sleeve, the contact friction can allow for load to be transferred from one riser to another causing an unequal load share, or load amplification, between the concentric pin and the twist. As the amount of riser twist increases the individual risers effectively join together to become a single cable - they become more tightly bound together and sliding lengthwise with respect to each other becomes more difficult. The risers only pull past each other when the CM is rocking (any change in attitude of the vehicle relative to the parachute risers). As the risers bend around the fairlead one or two of the risers must take a longer path. If there is a twist above the fairlead, the different risers have a longer path as the vehicle rocks. The friction between the risers in the twist redistributes the load in the risers in the region between the concentric pins and the twist. This phenomena is called twisted risers load amplification, and if it gets too large a riser could be overloaded and fail.

Each riser can safely support the load of the entire capsule during steady descent, but the load on the riser can be many times the capsule mass during inflation or disreef events. Only during those time periods could the twisted risers

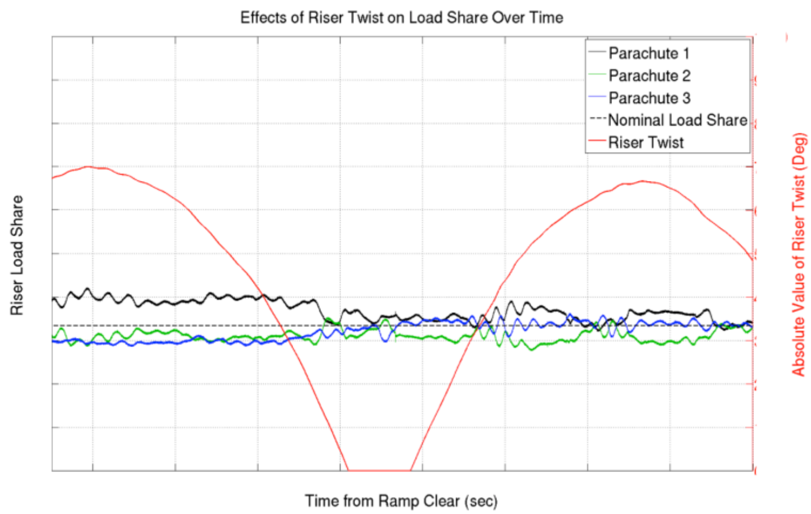

Fig. 5 Main Parachute Twist Angle and Load Share, CDT-3-5

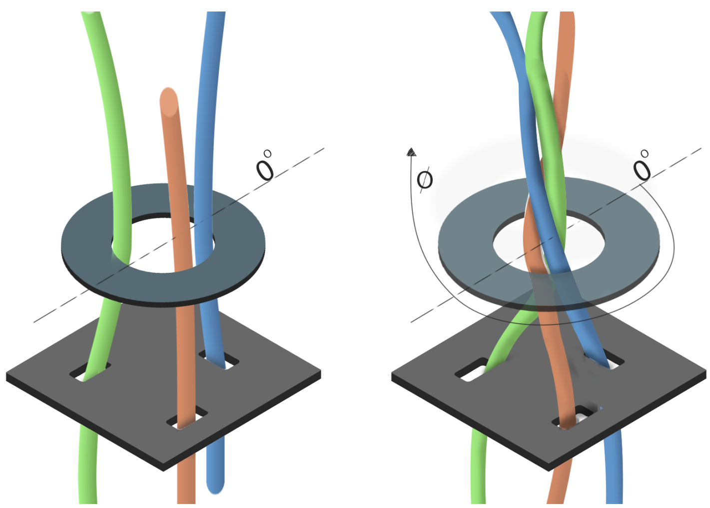

Fig. 6 Schematic of Twist Angle Definition

amplified load theoretically overload a riser.

The CPAS team has been tracking twisted risers load amplification as a risk for many years. Indeed, risers have been seen twisting around each other since project Apollo. During Parachute Test Vehicle (PTV) drop tests performed by CPAS, the system regularly experienced drogue and main riser twist accompanied by large amplitude rocking motion. Engineers on the CPAS and Orion Aerodynamics teams began to notice regular sinusoidal variations in the riser load data with a period that matched that of the vehicle's rocking. Initially an aerodynamic wake interaction between the vehicle and parachutes was considered. Engineers then made the correlation between twisted risers and the strength of the sinusoidal load variations (see figure 5), eliminating aerodynamic causes. No theoretical model was found that could predict load amplification of two or three cables twisted around each other and a series of experiments was initiated in early 2013.

The first set of experiments was to confirm that load amplification does exist when 2 or 3 risers are twisted together. A small scale facility was used to prove that load amplification exists and attempted to find trends with regards to twist angle, rocking angle, and rocking rate. Load amplification was measured, but it was determined that only a full scale experiment with flight-like components could produce results applicable to flight (see [2]). The CPAS program switched to textile riser extensions (from stainless steel cables) and protective sleeves were selected for the new components. A full scale test of the risers with various outer sleeve materials was conducted with twist angles from 0 to 1800°, but there was no fairlead (see [3]). Finally, a full scale test with a fairlead was conducted (see [4]). The risers did not have the flight-like concentric pins on the south end and they had been utilized for many tests. Also, the load measurement devices did not work correctly. Riser failure occurred causing testing to be stopped immediately. [5] notes that the failure can be attributed to very extensive testing (including use in previous test campaigns), low-fidelity riser construction, and low-fidelity attach point at the south end to reduce test costs. Lessons learned from those 3 experimental campaigns contributed to the tests described in this report. Experience gained from previous testing showed that flowerpot, fairlead, load measurement devices, and risers should be as flight like as possible and the number of cycles should be minimized to increase the chances of success and enhance the validity of the results.

In order to understand the likelihood of twisted risers load amplification damaging a riser, Monte Carlo performance simulations were run for many parachute configurations and mission profiles. Knowledge of the amplification factor as a function of twist angle is not enough to understand the risk to Orion - the factor must be applied to performance simulation results to determine the likelihood of a riser failing between the concentric pin and fairlead at peak loads. The analysis and results are presented in V.

II. Test Equipment

A photograph of the assembly with the primary components labeled is shown in figure 7. The north actuators are labeled LT1, LT2, and LT3, where LT represents load train. They are mounted on the facility strongback in a symmetric tripod configuration to mimic the maximum fly-out angles of the main parachutes during the inflation and disreef events. The rocking fixture includes many components. The rocking fixture base is bolted to the floor of the Structural Testing Laboratory with a tilt angle that aligns the axis of the fairlead hole at zero degrees rocking angle with the center of the symmetric tripod on the strongback. The rocking fixture turntable is mounted into a bearing on the base that allows it to rotate. There is a large sprocket on the underside of the turntable to which the chain is wrapped around. The rocking actuators pull the chain to effect rotation of the turntable. The fairlead plate and pin loader plate assembly are connected together via threaded rods and are not disassembled during the test. They function as the flowerpot and fairlead simulator for this test setup. They are mounted to the turntable via an adapter plate and two mounting plates. The risers are the final component of the full test setup.

A. Test Risers

Five test risers were manufactured according to flight tolerances. The test risers are similar to the riser extensions used in flight except that the north end is configured to mount on concentric pins rather than being looped through parachute suspension lines. The test riser's sleeve and south end assembly are identical to flight riser extensions. Regular inspection of the risers was accomplished between each load amplification test to determine the extent of damage to the outer teflon sleeve.

B. Fairlead and Gusset Simulator

The twisted risers load amplification test fairlead and gusset simulator approximately mimics the layout and geometry of the flight components. Figure 8 shows the assembly mounted to the turntable. The fairlead and pin loader plates were assembled with threaded rods and the distance between the plates was approximately the same as the flight assembly. The concentric pins and gusset choke holes were oriented similarly as well. The adapter plate was required to adapt the concentric pin layout to an older pin loader plate already manufactured for previous tests. The riser inserts were rounded brass guides upon which the outer layer of the riser contacts as it passed though the choke. The riser insert surface that the riser contacted had a similar radius of curvature and made the gusset hole the correct dimension. Using brass rather than titanium should not impact the objectives of this test. The divider plate and cover held the concentric pins in place during assembly and kept them oriented over the choke holes, similar to the flight gusset.

C. Load Actuators

The load actuators were used to provide a constant force on each riser of approximately 10,000 lb. As the rocking fixture rotated, the actuators were required to prevent over and under loading of the risers. These actuators were anchored to the strongback and connected to Dynema ropes which ran to the north end cradles. The actuators were placed on the strongback according to figure 9. This configuration represents the relative location of the risers during main parachute inflation.

D. Linear Actuators for Fairlead Rotation

The south fixture was rotated to ±90 or 60 degrees by linear actuators. These linear actuators attached to a chain that was wrapped around a sprocket on the underside of turntable. The position of the actuators was used to compute the rotation of the fairlead. During the week previous to testing, the system was tuned (with setup risers installed) to find the fastest rocking rate that the north end actuators were able to reasonable track. The peak rocking rate was determined to be 60 deg/s.

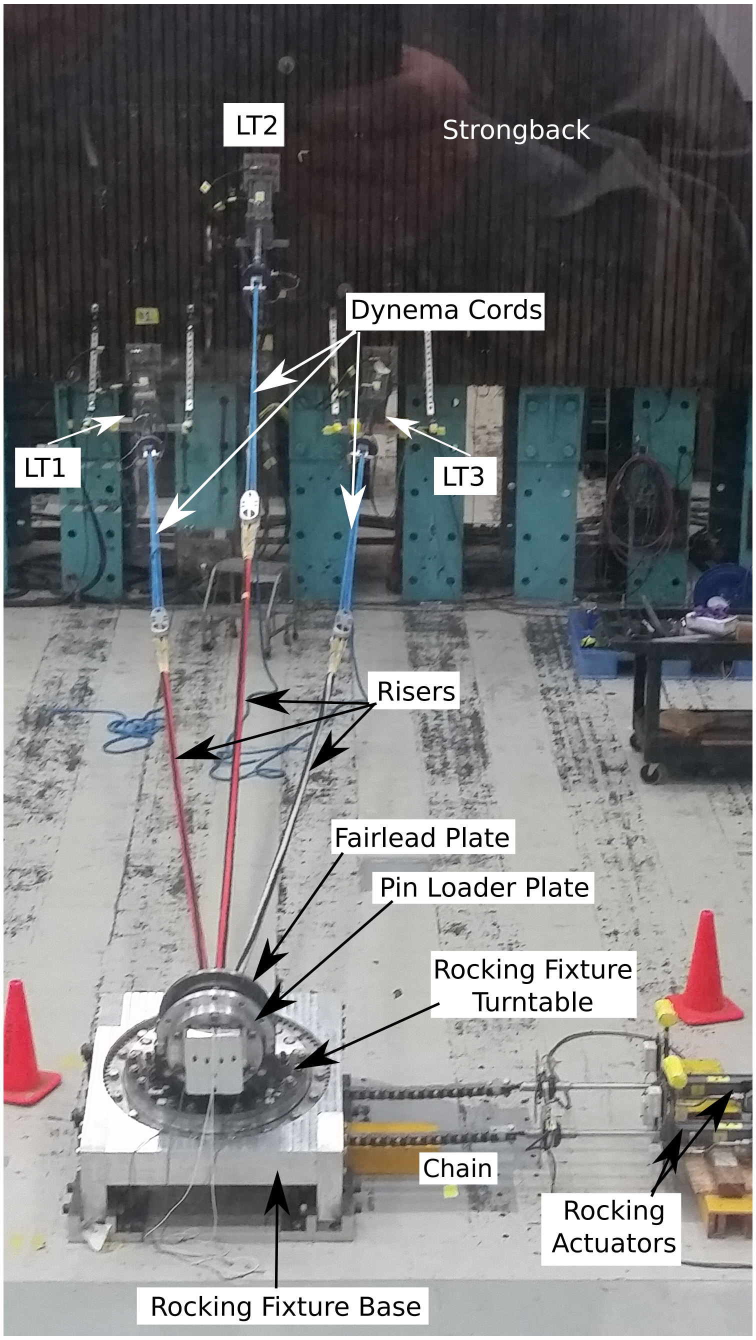

Fig. 7 Photograph from above of test setup

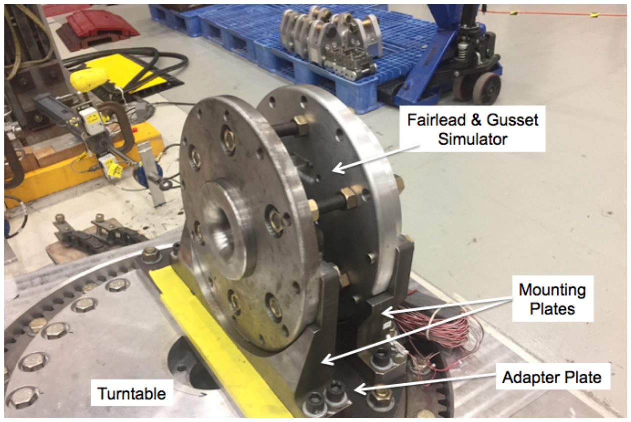

Fig. 8 Photograph of fairlead and gusset simulator installed on turntable

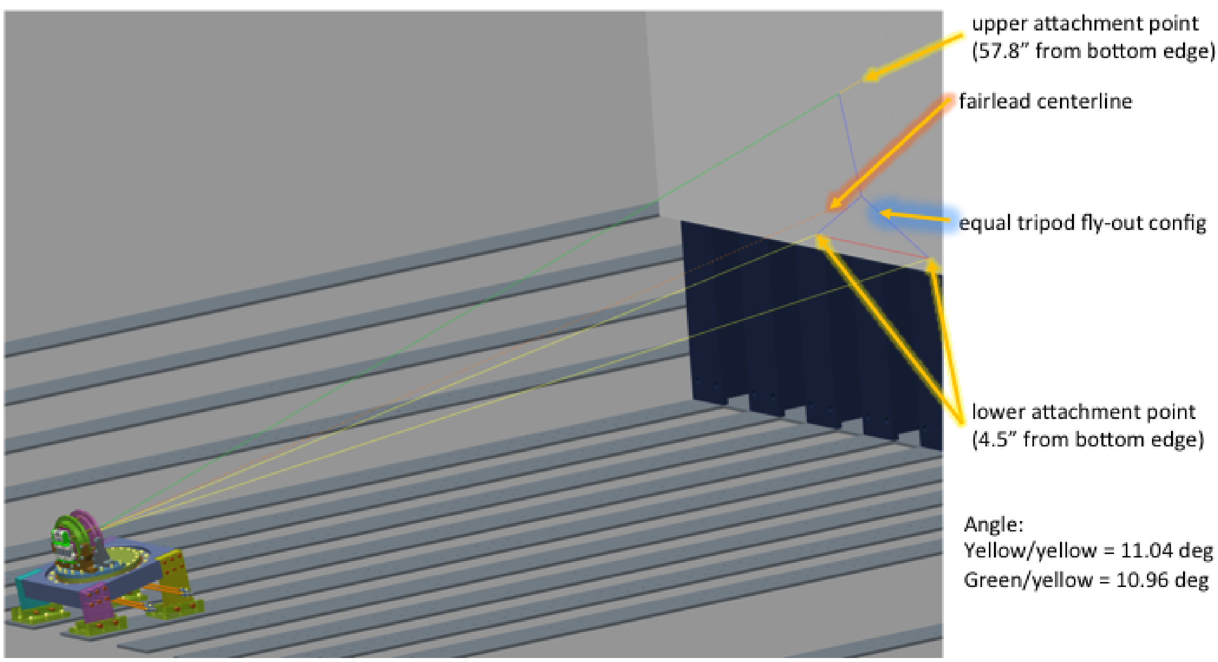

Fig. 9 Image of Actuator Layout from CAD.

III. Twisted Risers Load Amplification Test Results

Preliminary analysis showed that the load measurements became very repeatable after the first rocking cycle. Therefore, it was decided to reduce the number of cycles from 10 to 6 for each test condition and that the first cycle would be ignored. To speed up testing, the high, medium, and low rocking rate tests were combined into a single run. Six cycles at each rate would be run consecutively. The rates selected were 60, 30, and 15 deg/s. Unfortunately, one riser broke during the second test of the day (test 6 overall). All tests to that point had a peak rocking angle of 90°. The riser started breaking on the first cycle of test 6, but the effects weren't obvious until about the sixth cycle when a loud noise was heard. The risers had only survived 58 cycles, which was unexpectedly low.

The risers will not fail in this manner during flight or drop tests. Testing with large loads and large rocking angles is conservative and was expected to damage the risers - backup risers were purchased in advance in anticipation of riser damage. Inspection of risers from many previous drop tests has not found significant wear at the fairlead, while the twisted risers load amplification test risers have very large levels of abrasion with frayed lines and Kevlar dust at the fairlead. The damage at the fairlead is caused by the large normal force between the risers and the fairlead (and between the suspension lines themselves as they stack upon each other) and a small amount of relative motion along the length of the suspension lines. The rocking angle will rarely exceed 60° more than once or twice in an entire flight, and peak loads occur for only a few seconds of flight.

Evaluation of performance simulation and flight data showed that rocking angles greater than 60° occurs rarely and only once or twice per mission. Therefore, the peak rocking angle was reduced to 60° in an effort to increase the life of the risers. Then a quick evaluation of the load amplification profiles at three rocking rates showed that the highest rate produced marginally higher load amplification factors. To reduce the number of cycles on the risers, only the highest rate was used for the remaining tests. Both three and two loaded riser configurations were tested. The twist direction changed throughout the testing with clockwise (CW) measured looking from the rocking test fixture toward the north-end actuators.

A. Images of Testing

Figure 10 is a photograph of the twisted risers load amplification test setup with 3 risers twisted together immediately before pre-load was applied. Twisting was accomplished by disconnecting the risers at the actuator ends and manually twisting the risers around each other. The blue safety lines wrapped around the risers near the north end cradles were included to limit motion of the riser in the case of rapid failure, but were extremely loose and did not affect the loading or fly-out.

GoPro video cameras were used to capture the motion of the risers relative to each other and within the fairlead for the first 16 tests, in addition to overall videos recorded by the STL team for all of the tests. One of the GoPro videos looked directly along the axis of rotation of the rocking fixture. Those videos clearly show the risers being pulled past each other throughout the rocking motion. Figure 11 shows screen captures of the risers at the two extremes of rocking and the zero rocking angle. The zero rocking angle is shown in the top image, with the vertical blue and orange lines indicating the relative position of the riser sleeves. Close up inspection shows the serial number markings for the two risers in view at that location. The bottom two images show the relative change in location of the risers as the fairlead rocked. The riser with the longer path around the fairlead had pulled past the other risers during the rocking in that direction.

B. Load Amplification vs. Rocking Angle

The facility actuators (Load Trains 1,2, and 3) were configured with a PID controller to attempt to maintain a constant load at the north end of the risers. The actuators were able to maintain the load within 10% of 10,000 lbs while adjusting for the changing location of the risers at the exit of the rotating fairlead. The north-end actuators had to move a few inches to maintain load during a rocking cycle. Therefore, the total load is not constant and the load amplification must be normalized by the applied loads at the north end. The applied load was measured at each actuator and recorded using the same data acquisition system that was monitoring the load bars and rocking angles. The load amplification is calculated for each riser as the scaled load measured by the load bars divided by the measured load at the upper end, not considering the loads of the other risers. The load share is calculated as the scaled load measured at the load bars divided by the total load measured on all three risers at the upper end. The load amplification factor and load share can be plotted as a function of rocking angle.

figs. 12 to 14 show the load amplification versus rocking angle for all of the successful tests. Each riser is plotted separately, as shown in the legends, with multiple line types (solid, dots, or dashes) to indicated different rocking rates.

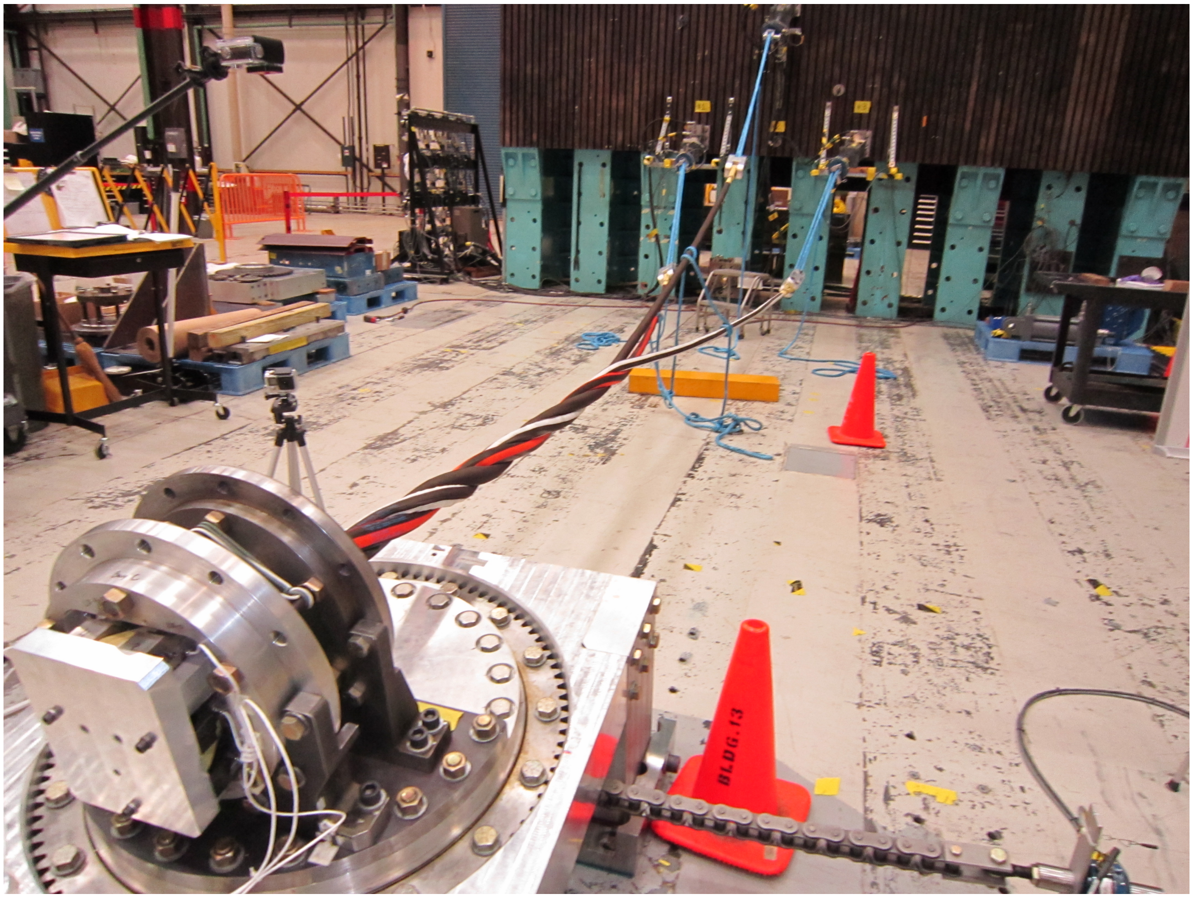

Fig. 10 Photograph of Twisted Risers in Test Setup

The tests conducted at only 60 deg/s had a $\frac{1}{4}$ cycle of data recorded at the end as the rocking fixture returned to zero rocking angle at 2 deg/s. Those data are shown to indicate that very low rates do not affect the load amplification values. The tests conducted at three higher rates (figs. 12 to 13) also show very little difference in load amplification as a function of rocking rate. The small oscillations in load amplification factor are due to "jitter" in the rocking fixture as it rotated. The small oscillation in rocking rate appears as oscillation in load because the north-end actuators were attempting to hold constant load but could not account for that motion.

The load amplification factor is a function of rocking angle and location of the riser in the fairlead with respect to rocking axis. For example, in test #7 (Figure 12), the bay B riser load factor decreases quickly as rocking angle increases from -50 to 50°, while bay E has the opposite trend. Bay C has a relative small load amplification factor because of its location in the fairlead. The riser with the higher load amplification factor has the longer path around the fairlead radius and get stretched more as rocking angle increases. Generally the maximum load amplification factor occurs at the peak rocking angle as the riser continues to be pulled.

The twist amplification values quickly increase with rocking angle. It is difficult to determine what the load amplification would be if vehicle was rocking only 10 or 20° . Because of this lack of data, the load amplification factor as a function of peak rocking angle isn't developed.

C. Load Amplification and Load Share Models and Results

The twisted risers load amplification factor derived in this subsection is independent of rocking rate and peak rocking angle. The amplification factor is only dependent on the absolute value of twist angle and the number of loaded risers. All experimental evidence found that the difference in load amplification between different rocking rates is negligible in the range of 2 to 60 deg/s. Without more test data, the load amplification factor must be assumed to be independent of

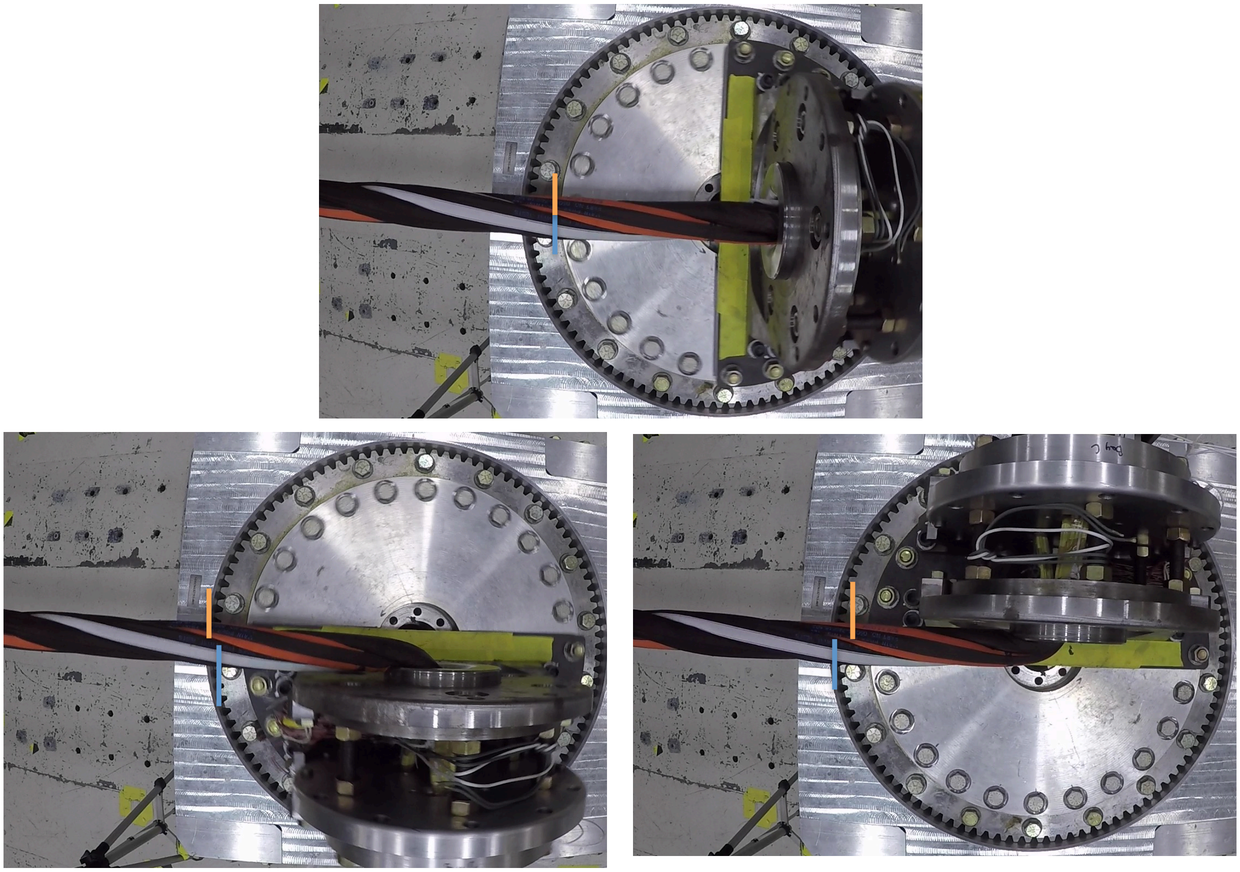

Fig. 11 Relative Position of Risers at 3 Different Rocking Angles

rocking rate for rates greater than 60 deg/s. No tests were conducted with smaller than 60° degree peak rocking angles. More experiments with smaller peak rocking angles are required to better understand the dependence on peak rocking angle. Therefore, the largest load amplification factor was selected from each test.

Load amplification and load share are calculated differently, but give similar results. The largest load share value should be approximately $\frac{1}{3}$ of the load amplification value. Any differences are due to load share using the total load at the north end and load amplification only considering the load applied at the north end of each riser. The applied loads should be very similar, but the facility had some variation in load as the actuators attempted to keep up with the moving fairlead.

The greatest load amplification factor of each loaded riser for each test run was selected to be used in a linear least squares curve fit to find an expression for load amplification factor as a function of twist angle. The markers in figs. 15 and 16 represent the peak load amplification factor of each riser for each twist angle tested, but only the highest of the 3 was used in the fit. The best fit curves and 3σ upper bound curves are shown for the 3 riser data. The 2 riser data did not have enough data sets for the Python polyfit function to determine a covariance of the fit, therefore the 3σ offset from the 3-riser data was used to increase the value of the amplification factor. Preliminary analysis of the performance simulations had shown that load amplification would not impact the margin of safety of the main risers, so the maximum conservatism of 3σ was felt to be appropriate.

Load share is a convenient metric for comparing with some older reports and for considering how close an individual riser can be to supporting the total cluster load. The maximum load share values measured in the experiment are shown in figs. 17 and 18. The least squares linear fits as a function of twist angle are also shown. It can be seen that the load share (and load amplification) is not evenly balanced between the risers at zero degrees twist. The conservatism is due to both the load bar scale factor accounting for fairlead friction and the 3σ curve fit.

The original expectation was for the load share function to exponentially approach the value of 1 (as seen in figure

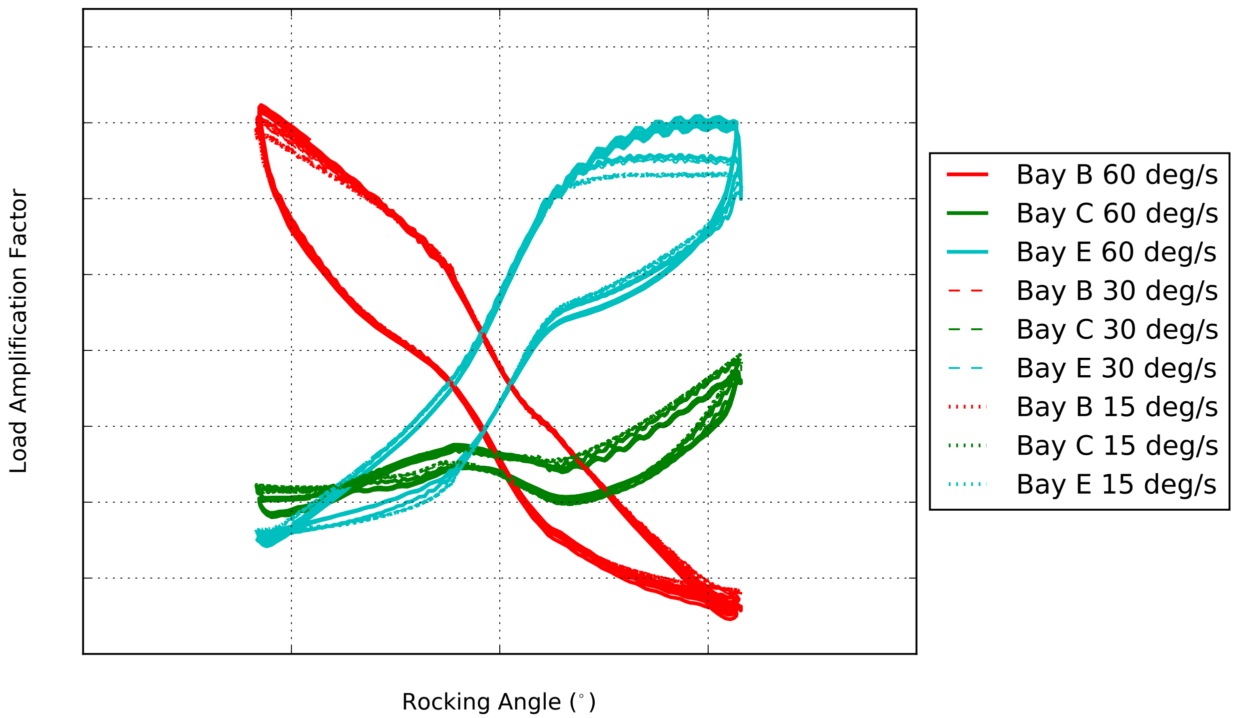

Fig. 12 Measured Load Amplification, Test # 7, 1800° Twist Angle

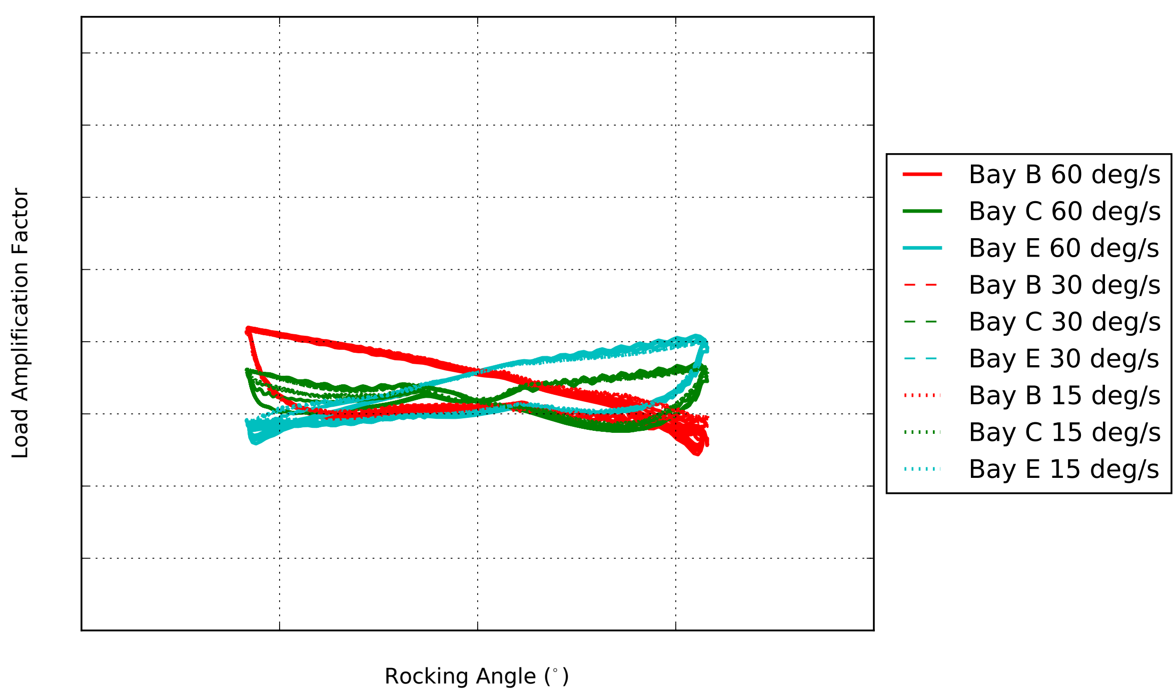

Fig. 13 Measured Load Amplification, Test # 8, 360° Twist Angle

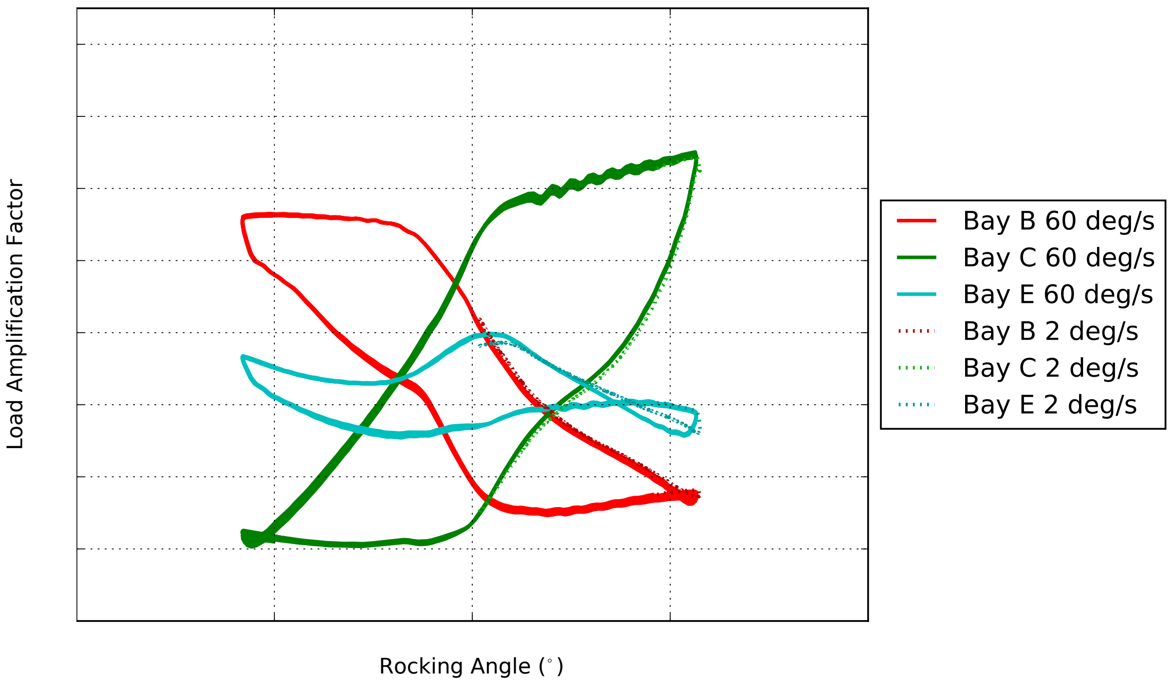

Fig. 14 Measured Load Amplification, Test # 25, 1380° Twist Angle

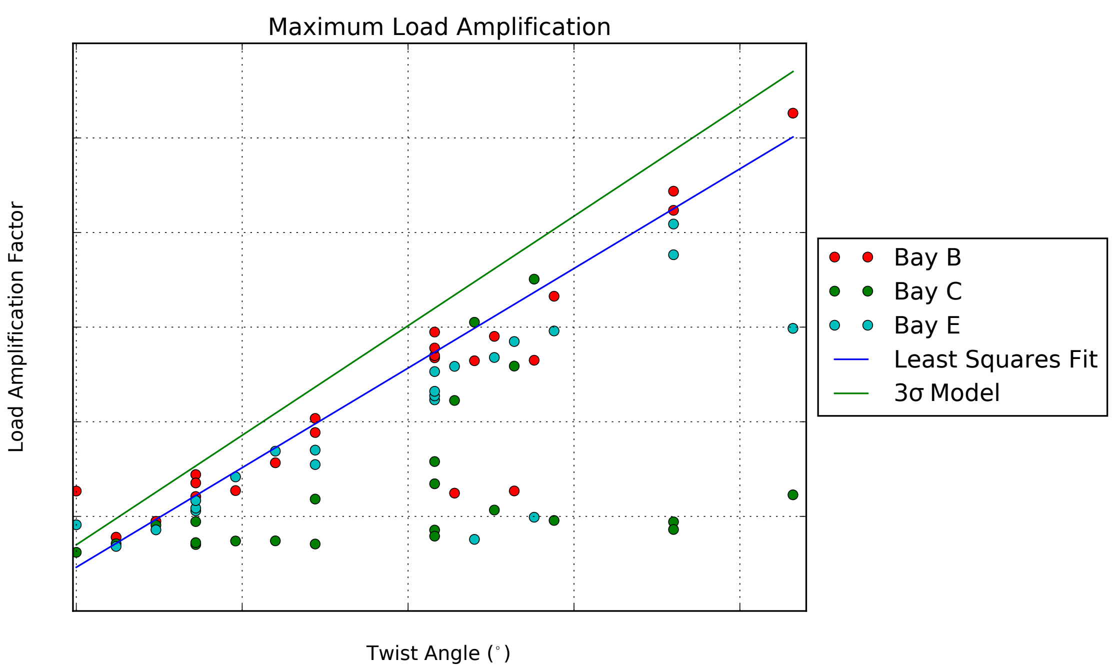

Fig. 15 Three Main Riser Peak Load Amplification

19 from previous subscale experiments), but the raw data clearly have a linear nature. One might note that although the load amplification factor is large at six full turns, the load share is approximately 0.6. Previous experiments reported

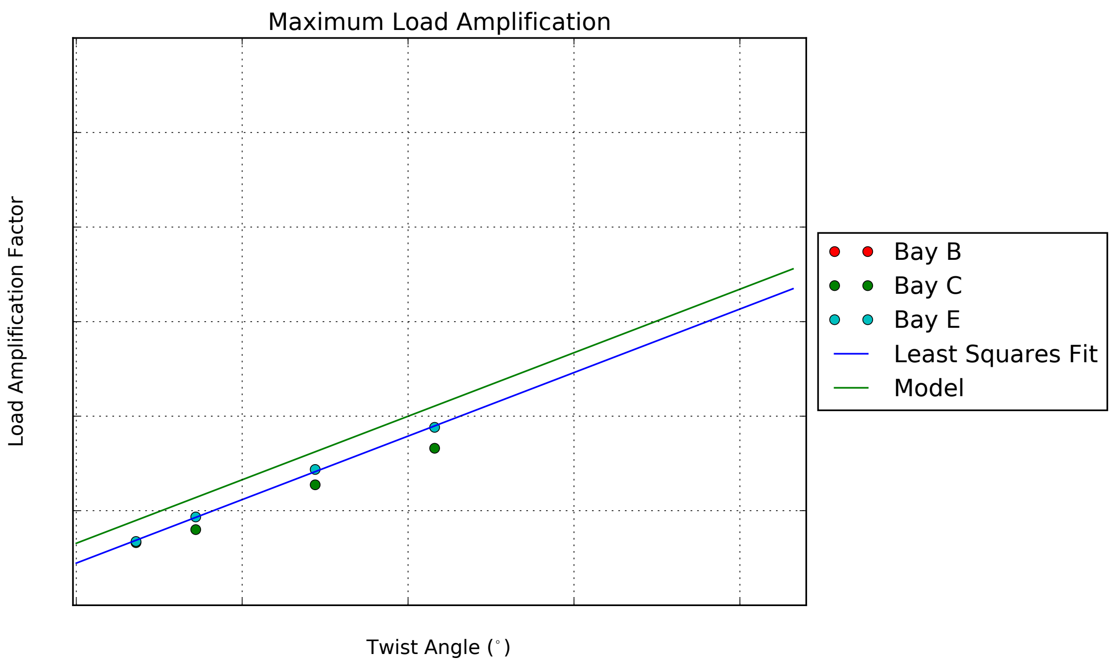

Fig. 16 Two Main Riser Peak Load Amplification

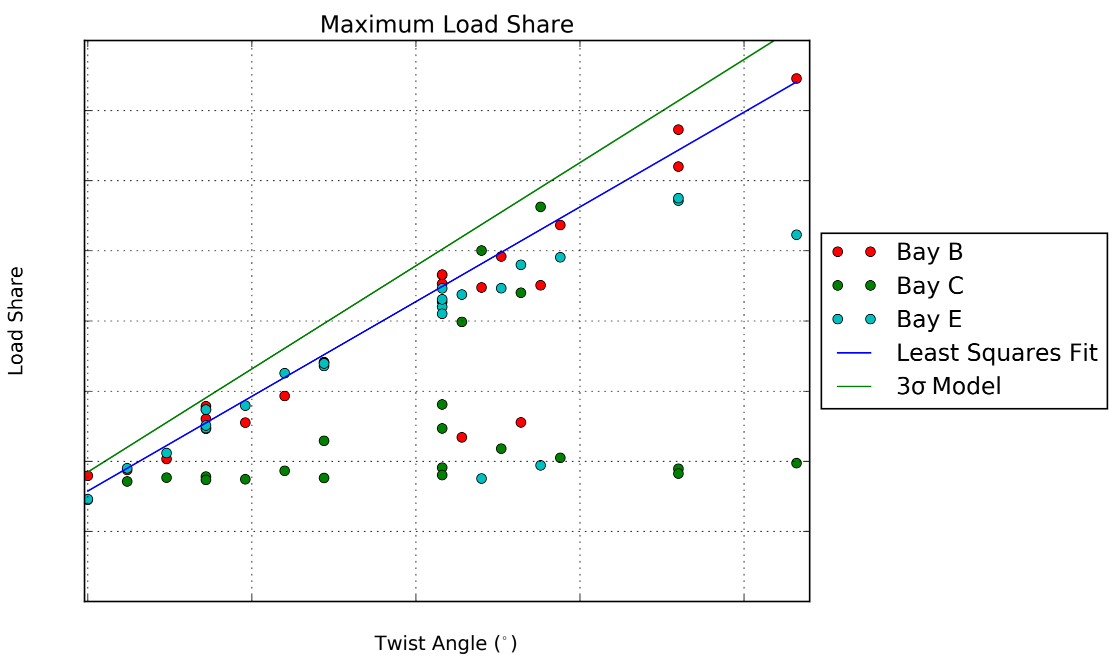

Fig. 17 Three Main Riser Peak Load Share

load shares up to approximately 0.9 and only near the greatest value load share did the exponential become obvious. One could argue that for load shares less than approximately 0.75 the trend is linear. Only when the load share is above

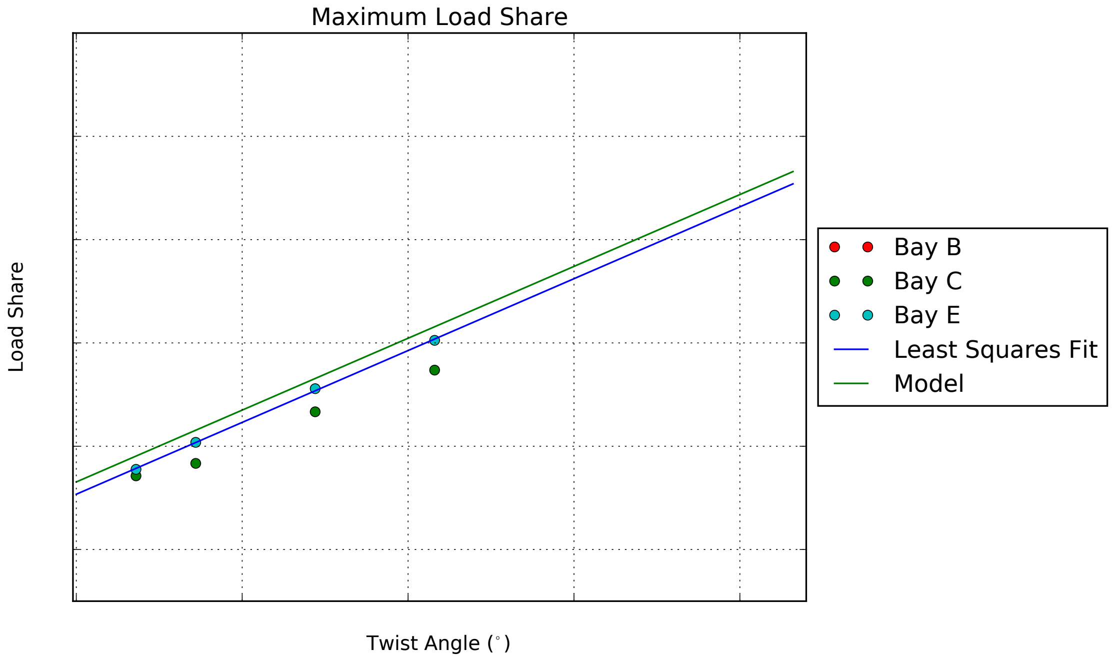

Fig. 18 Two Main Riser Peak Load Share

0.75 does the exponential appear, based on the subscale data.

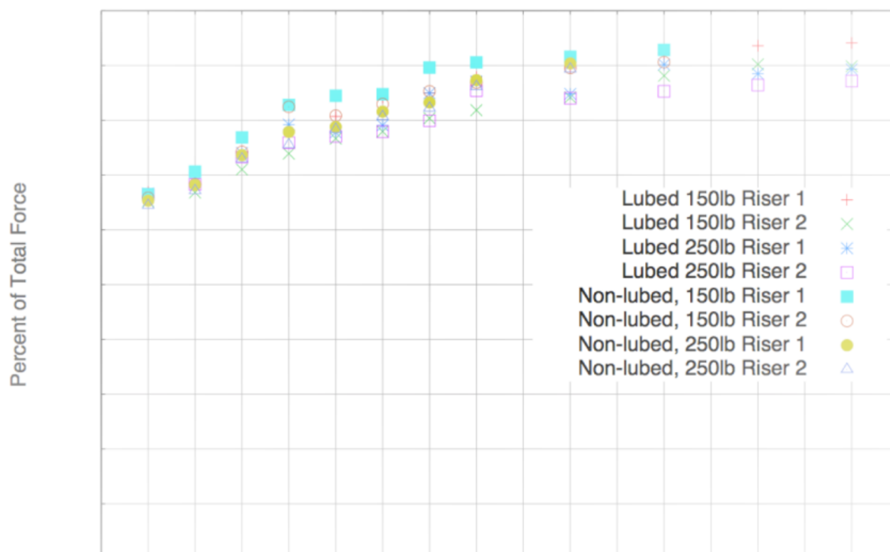

Fig. 19 Subscale Twist Amplification Test Results Showing Exponential

IV. Assessment of Orion Riser Margin

The main riser strength was found to have a large margin of safety when accounting for twisted risers load amplification. Only one case out of 144,000 Monte Carlo simulations had amplified loads within 5,000 lbs of the zero margin riser strength, and that case would not be included in the minimum design set of cases utilized for success criteria analysis. Also, the maximum load in the minimum design set was approximately 28,000 lbs less than the zero margin strength of the main riser.

V. Conclusion

The test hardware was as flight-like as possible. The risers were identical to flight risers in the region near the fairlead. The fairlead was exactly the same shape and roughness as the flight fairlead. The flowerpot geometry was very close to flight-like. The risers were installed in flight concentric pins within the flowerpot. The load amplification factor can only be determined using flight-like components, and the experimental setup allowed for the best possible measurements.

The load amplification factor was found to be linear with twist angle with the factor being relatively large at only a few full turns. A dependence on peak rocking angle could not be determined from the test data. The tests should have been run with a range of peak rocking angles at each twist angle. The results presented in this report are valid, but conservative. If data were available at smaller rocking angles, then a peak rocking angle dependence could have reduced the load amplification factor for many cases.

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